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Universal and Dynamically Reconfigurable Sensor Interface in Lab-on-Spoon Multi-Sensor System

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Abstract: Surging application fields of integrated electronics and sensors, as e.g., automation, internet of things (IoT), cyber-physical(-production) systems (CP(P)S), or Industry 4.0, require more able, versatile, and dependable sensor electronics and systems. In particular, cost effective features of self monitoring, -calibration, trimming, or -healing are sought after. State-of-the-art integrated components for sensor signal conditioning are usually not generic and dedicated to specific sensors or applications and are not offering self-x capability. Thus, based on a survey of existing solutions, a universal sensor interface IC with self-x features has been developed in a first step toward meeting this growing demand. In this paper, our universal sensor interface with self-x properties (USIX) chip will be described and exemplary application in a multi-sensor scenario for food quality and safety assessment with competitive recognition results will be presented.

Key words: Impedance spectroscopy, integrated sensory systems, generic sensor electronics, Self-x properties, food analysis

Introduction

Designing multi-sensory systems commonly includes the development or application of very specific sensor electronics for signal conditioning, where electronics have to effectively pick--up and transduce the sensor's signal output for potentially very heterogeneous sensing principles and requirements. Especially in embedded/integrated intelligent multi-sensor systems, e.g., IoT, CP(P)S, or Industry 4.0, sensor electronics can easily increase a system's complexity and size, in consequence becoming a significant factor to effort and cost. This fact is aggravated by the increasing demands on electronics and sensory systems dependability and the correspondingly required self-x-capabilities. There are signal conditioning ICs in the market, where certain properties can be configured, e.g., amplifier gain and offset, to help reduce the demand for specific electronics and allowing a broader range of applications. However, most of these devices still possess very limited capabilities, as they are usually designed for only one category of sensor signals. Thus, in this research an architecture and a chip was designed, manufactures and tested, that realizes generic multi-channel sensory signal condition and conversion with first self-corrective capabilities.

State of the Art Sensor Signal Conditioning ICs

A summarizing overview of commercially available sensor signal conditioners with programmable features or reconfiguration capabilities is given in *Tab. 1* from manufacturers' datasheets. Examples are the Analog Devices AD8557 [1], Texas Instruments' PGA308 [2] or the MLX90308 from Melexis [3]. They all have one input channel to read out voltage signals and share the ability to manually set gain and offset values. Some products like the LMP90100 from Texas Instruments [4] also include different channels, making multiple implementations redundant. However, most of these ICs can process only one type of sensor signal like voltage, current or capacitance. A research of commercially available signal conditioners revealed only one product, the Smartec UTI [5], which can handle voltage and capacitance inputs.

Tab. 1. Overview of existing sensor signal conditioner IC with reconfiguration capabilities.

Manufacturer	Components	Input Signal	Reconfigurable Features	Channels
Analog Devices	AD8231, AD8250, AD8251, AD8253	Voltage	Gain	1
	AD8556, AD8557	Voltage	Gain, Offset	1
	AD7798/9	Voltage	Gain, Digital Outputs	3
Texas Instruments	LMP90100	Voltage	Gain, Offset, Sensor Supply	4 differential or 7 single ended
	INA333, PGA280	Voltage	Gain	1
	PGA308	Voltage	Gain, Offset	1
Maxim	MAX4208	Voltage	Gain	1
Semtech	SX8725	Voltage	Gain, offset, Resolution vs. Speed vs. Current	1 differential or 2 single ended
Melexis	MLX90308	Voltage	Gain, Offset	1
ZMDI	ZSSC/ZSC-Series	Voltage or Capacitance resp.	Gain, Offset, Sensitivity, Temperature	1
iC-Haus	iC-TW3, iC-HO	Voltage	Gain, Offset, Temperature	1,3
acam	PS08, PS081, PS09	Resistance	Current vs. Speed vs. Accuracy, Gain, Offset, Temperature	1-4
Smartec	UTI	Resistance, Capacitance	Gain, Offset	1-5

Tab. 2 USIX self-x features for chip and connected sensors.

Self-monitoring	Self-calibrating	Self-repairing
• Chip temperature • Sensor temperature • Sensor power consumption / supply • Transistor aging • Measurement range	• Offset voltage • Sensor temperature • Voltage/current supply of sensors • Measurement range	• AMR sensors (flip current) • MEMS switches (heat actuator)

A Universal Sensor Interface

To better meet the application demands discussed above, a universal sensor interface with self-x properties (USIX) has been developed in the form of a single integrated CMOS circuit [6]. It is suitable for voltage, current, resistance, capacitance, inductance and impe- dance inputs and can connect with up to nine different sensors. Dynamic self-correction, reconfiguration, and application-specific programming enable the USIX chip to meet expectations and required specifications of named application fields. As a result, development time as well as system size can be minimized.

The IC's flexible structure allows setting up intelligent systems with self-x capabilities, e.g., self-calibration or self-monitoring. The main self-x features are listed in *Tab. 2*. Its functionality relies on several different circuit concepts [7] [8] [9] [10], some of which are employed for the first time, like a precision instrumentation amplifier or a new kind of temperature sensor. To understand the functional principle, *Fig. 1* depicts a simplified block diagram of the USIX architecture. The current USIX chip reads out connected sensors sequentially through an input multiplexer to reduce die area and in consequence cost. Modularization, e.g., replicating the conditioning blocks for synchronous multi-channel reading, has been considered, but not implemented in the first silicon. At the same time the IC is able to supply sensors and external structures with reference signals like voltage, current or AC signals. Those signals can be adjusted, e.g., based on the sensor's last read-out. After signal conditioning, output data will be provided in 10 to 12 bit digital representation or analog signal, according to user specification. Furthermore, it is possible to measure the supply pins of connected devices and gain knowledge of their current state or power consumption. The chip's configuration is stored in an internal register and can be programmed and controlled via an external microcontroller. The USIX IC has been implemented in 0.35 µm CMOS technology (*Fig. 2*).

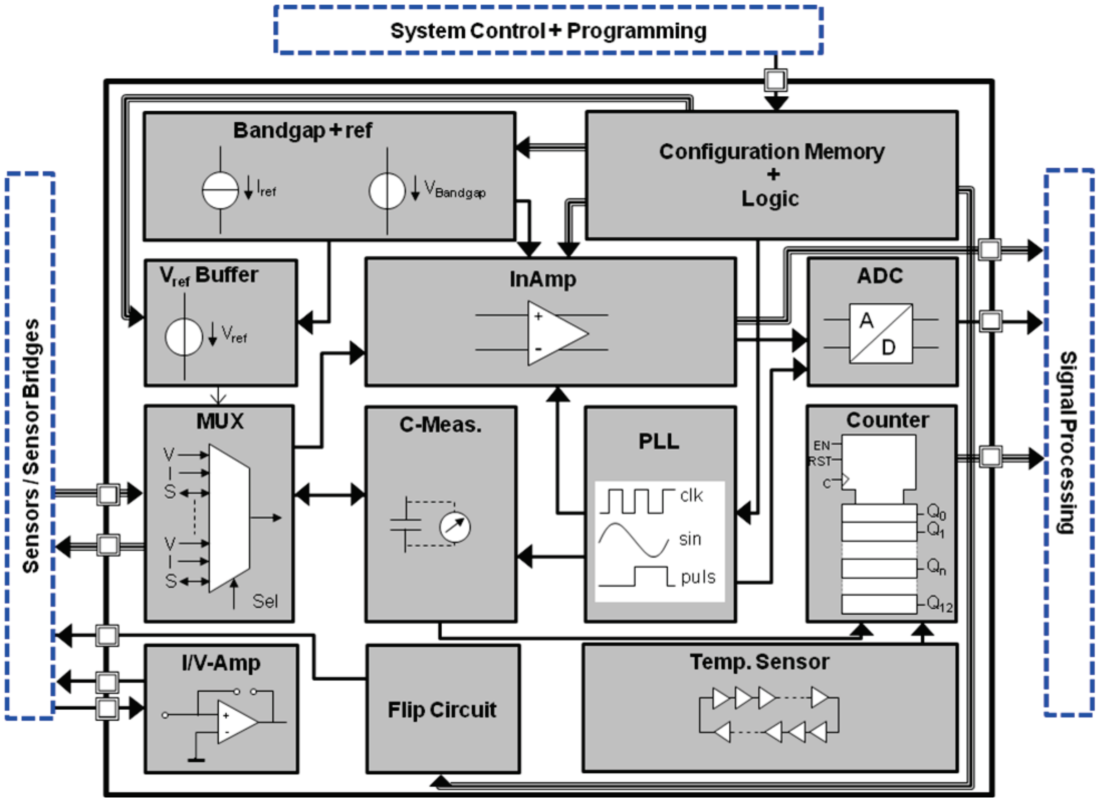

Fig. 1: Block diagram of the USIX chip architecture

Concept of a Lab-on-Spoon System

Due to the high adaptability of the interface and its functional quantity, it can be applied in versatile systems. One example application that capitalizes on the USIX characteristics is an ongoing research project concerning a Lab-on-Spoon system [11] [12]. The purpose of this project is to create an assistance system for food safety and monitoring among others. Classification of liquid substances is achieved by physical and chemical analysis. The Lab-on-Spoon is a multi-sensor system, which is integrated in a spoon-shaped 3D printed package where the spoon cavity contains different sensors. Current prototypes include a Pt10000 temperature sensor, RGB color sensor and two electrodes for impedance measurement. It is capable to asses and distinguish different liquids, for example pure wine from wine that has been contaminated with glycol or the freshness or rotting state from milk. Each sensor is equipped with individual, substantially different read-out electronics on separate circuit boards. Data acquisition and system control are carried out by a microcontroller. In total four PCBs provide all necessary electronic components. This heterogeneous system is a perfect case study for the versatility of the USIX chip.

USIX in Lab-on-Spoon Application

Opposed to earlier setups, which contain the above mentioned extensive amount of sensor electronics on up to four PCBs, a system has been set up where signal conditioning and system control is solely achieved by a single USIX-IC combined with a microcontroller. For USIX-prototyping and measurement, a dedicated Lab-on-Spoon (LoS) front-end has been used that doesn't contain any electronics but the sensors, with their contacts led to the outside through the spoon's handle (*Fig. 3*). The temperature sensor is an UST Pt10000, two galvanized metal pins are used as electrodes for basic impedance spectroscopy purposes, and for color sensing a MAZeT MRGBiCS RGB sensor has been employed. A white LED serves as an

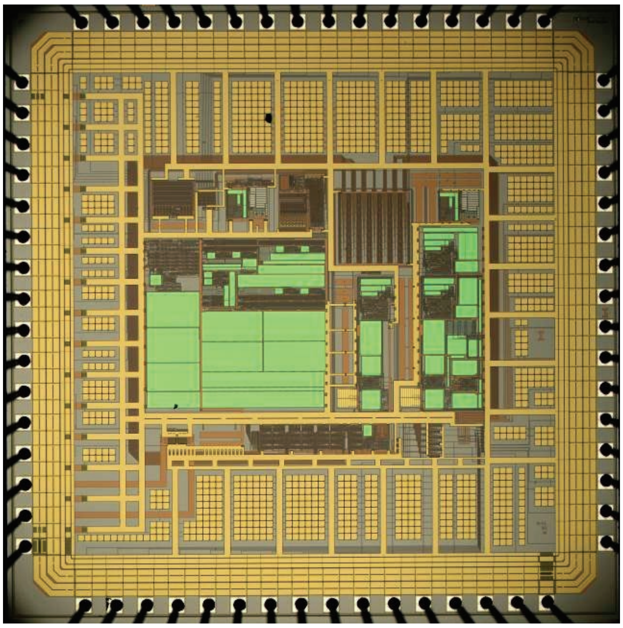

Fig. 2: USIX die manufactured in 0.35 µm CMOS technology with 64 pads and 11.6 mm²

active illumination source. To combine the front-end with the interface it has been connected to an USIX prototyping platform that contains the IC, a microcontroller and some non-essential hardware like display and breadboard (*Fig. 4*). A scaled-down version of the system, e.g., based on USIX dies and Chip-On-Board (COB) technology, could be integrated inside the spoon's case in later setups advancing toward a versatile and self-x Lab-on-Spoon system instance.

Experiments and Results

The USIX-IC has been configured to read the signals of each sensor from the LoS front-end. *Fig. 5* illustrates the corresponding measurement arrangement.

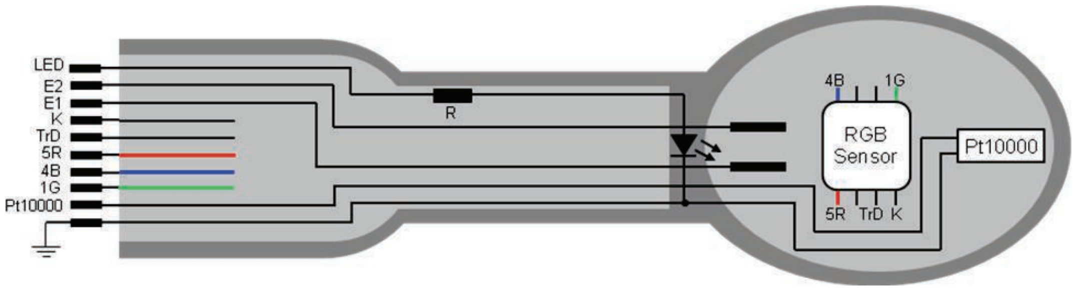

Fig. 3: Schematic illustration of the USIX Lab-on-Spoon front-end.

The temperature sensor is part of a Wheatstone bridge where the output is picked up by the interface. The three channels of the color sensor are connected to resistors where the generated photo current leads to a voltage drop that can be measured by the USIX instrumentation amplifier. Three 100 Ω resistors are integrated inside the IC and can be used for this purpose. Optionally, if different values are desired, also external resistors can be used. Due to the low currents from photo diodes, 560 kΩ were used in this case to get higher voltages and resolution. The sensor's isolation diode is connected to a fixed potential. During measurement, the LED is turned on by the microcontroller. For impedance measurement, a FFT is performed on the sampled signal (1 MS/s) by the microcontroller. The following frequencies are evaluated with an amplitude of 1.1 V: 0 Hz, 0.977 kHz, 2.93 kHz, 15.625 kHz, 46.875 kHz,

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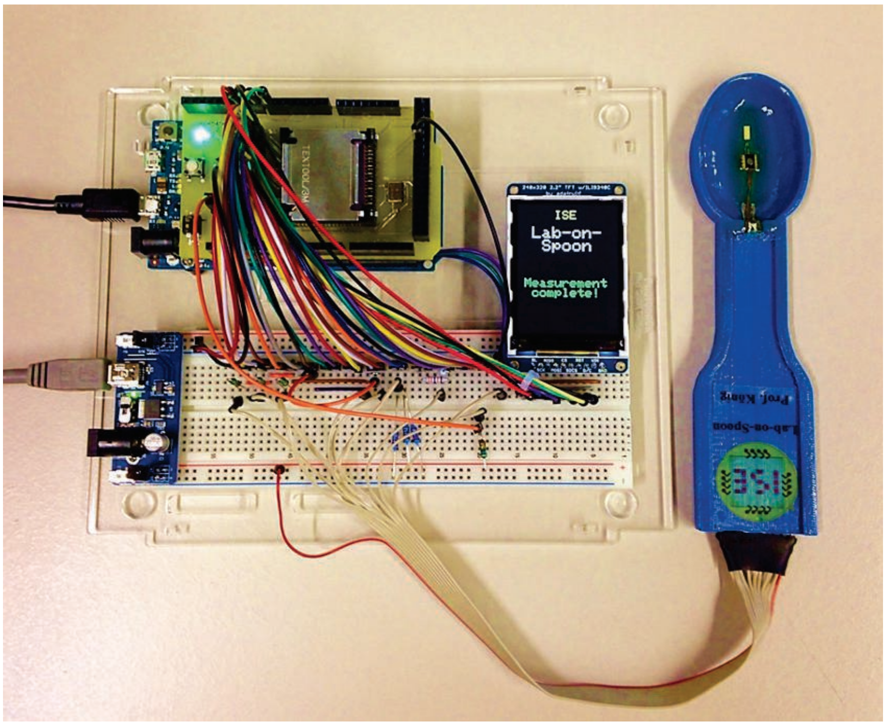

Fig. 4: Test setup of USIX Lab-on-Spoon system based on Arduino

and 125 kHz. Thus, a basic impedance spectroscopy measurement could be achieved.

Since the USIX system has self-monitoring and –calibration capabilities, compared to earlier prototypes, the functional range of the Lab-on-Spoon can be enhanced. An auto-calibration mode has been implemented for the RGB sensor which chooses the optimal range after performing a reference measurement. This concept can also be applied for other sensors, e.g., the Pt10000. The temperature range can be narrowed down to the relevant interval, increasing resolution in turn. Theoretically, temperature ranges between 0.98°C and 98°C are possible with a 10 bit resolution of the internal ADC.

Experiments were performed with different liquids. For evaluation, measurement data was assessed with the pattern recognition software QuickCog [13] that maps multi-dimensional data to two-dimensional diagrams. Measurement was repeated in several cycles and the acquired information was processed by the software. *Fig. 6* visualizes clearly distinguishable results for distilled water, tap water, soy sauce, and vinegar, which are competitive to the results of the previous LoS prototype generation with discrete electronics.

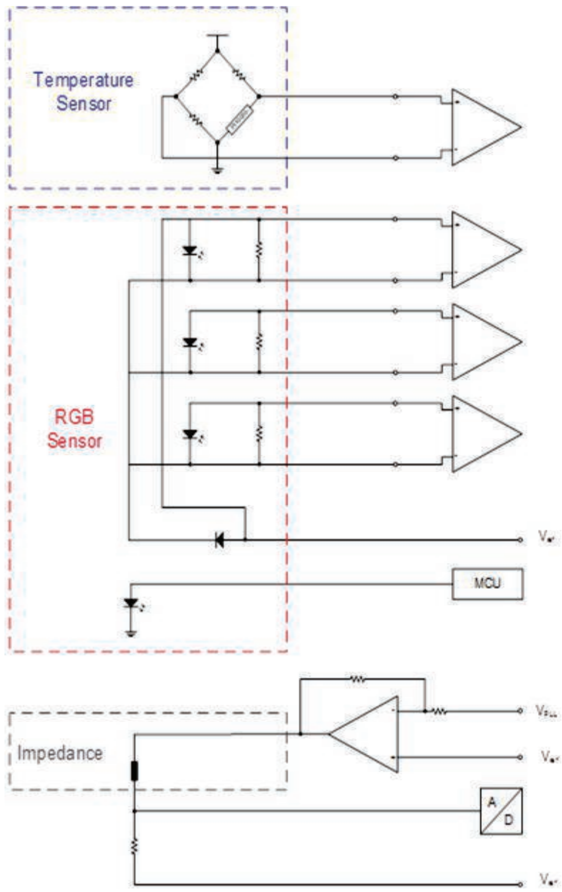

Fig. 5: Schematic of USIX Lab-on-Spoon system measurement setup.

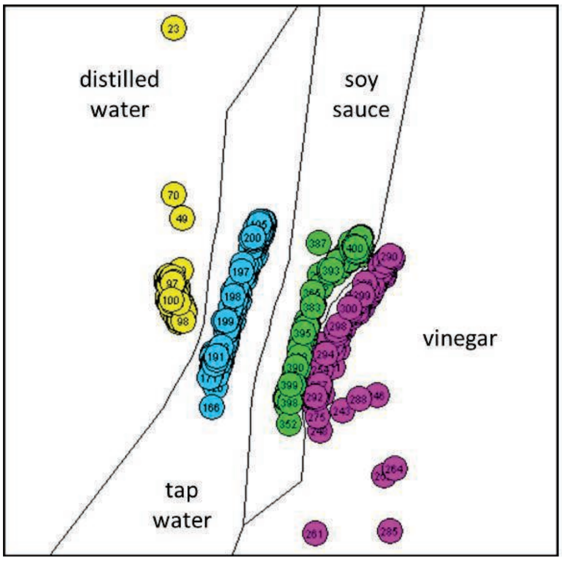

Fig. 6: Resulting well-separated feature space of measured sample liquids.

Conclusions

IoT, CP(P)S, Industry 4.0, in-line measurement etc. impose increasingly stringent demands on versatility, dependability, cost, power dissipation, and size of sensor electronics and systems, which cannot be met by state-of-the-art integrated sensor signal conditioners. Thus, in our research the design and implementation of such next generation generic and self-x sensor electronics is pursued. The universal sensor interface USIX is the first prototype from this research activity. It can be used in a vast amount of multi-sensory systems, providing intelligent self-x features and reducing system size, complexity, power, and cost. To proof the IC's function and to advance an ongoing research project, it has been combined with a Lab-on-Spoon front-end and successfully delivered competitive results. In addition to reduced hardware overhead, the USIX Lab-on-Spoon system has reconfiguration capabilities that can be used for self-calibration and to adjust measurement ranges. Due to the flexibility of the interface, the same hardware can be adapted for later prototypes that comprise potential modifications of the analog front-end. Further, actuator capabilities are already included in USIX, which allow additional self-x features, e.g, flipping or possible compensating of AMR sensors.

In future work, USIX application in magnetic localization of integrated data loggers will be further elaborated and presented.

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